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13. ABSTRACT *(Maximum 200 words)*

Work was studied on power combining applications using coplanar waveguide (cpw)-fed slot antenna oscillators. In this work, a large amount of oscillators are combined together to result in a high power source. The problems encountered with such systems is the non-linear interaction in the coupled-oscillators. As a single oscillator, we use a slot-antenna with a single microwave transistor designed to oscillate at 20 GHz. We have successfully combined a 2x2 array of these slot-antenna oscillators at 20 GHz to generate a total radiated power of 70 mW with a dc-RF efficiency of 15%. The power combining efficiency was 100%. Since the antennas are placed on a dielectric lens and therefore result in a high-gain pattern, the effectiive radiated power is around 4.5W. This configuration does not suffer from substrate mode problems and therefore can be easily extended to 94 GHz power combining systems.

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Theoretical and Experimental Study of Low-Loss, High-Efficiency Monolithic Antenna Structures at 94 GHz

Linda Katehi and Gabriel Rebeiz

Final Report

CONTRACT IDENTIFIERS

ARO Proposal Number: 28483-EL

Period Covered by Report: 6/91 to 12/94

Contract Number: DAAAL03-91-G-0116

Name of Institution: University of Michigan

Scientific Personnel Partially or Fully Supported by this Contract:

Faculty	Students
Linda Katehi	Andy Engel (Partially Supported) Emilie T. van Deventer (Partially Supported) Kazem Sabetfakhri (Fully Supported) George Ponchak (NASA Lewis Fellow)
Gabriel Rebeiz	Curtis Ling (Fully Supported) Brian Kormanyos (Partially Supported)

STUDENT PROFILES

This contract supported students part-time as well as full time. A short description of this partial support and the relevance of the students work with the subject is described below:

Emilie T. van Deventer, now an Assistant Professor in the Electrical Engineering Department of the University of Toronto. She graduated with a Ph.D. in the summer of 1992. She was supported full time during the last year of her studies due to the relevance of her subject to this contract. Specifically, she initiated the study of dielectric waveguides using an integral equation formulation which led to the use of wavelets. That subject was pursued by Kazem Sabetfakhri.

Andy Engel, now a staff engineer with Motorola, Central Research Laboratories, Phoenix, AZ. He graduated with a Ph.D. in the winter of 1993. He was supported part time by this contract. His subject was also relevant to the contract as he was able to specify dielectric waveguide geometries which have been used for the development of a leaky wave dielectric waveguide antenna.

George Ponchak, expected to graduate in winter 1996. He is supported by a NASA Lewis fellowship and has worked on the development of dielectric waveguide antennas since May 1992. He will continue working on this subject until his graduation.

Kazem Sabetfakhri, expected to graduate in May 1995. He has been supported fully by this contract. Since June 1994 he has been funded by a University fellowship. His work has been concentrating on the use of multiresolution analysis for the study of dielectric waveguide problems. Presently he applies this theory to microstrip patch antennas.

Curtis Ling, now an Assistant Professor and Head of the Wireless Laboratory, Hong Kong University of Science and Technology. He graduated with a Ph.D. in summer of 1993. He was supported full time by this contract and his work concentrated on the development of a 94 GHz planar monopulse receiver.

Brian Kormanyos, now a staff engineer with Hughes Space Communication Group, Los Angeles, CA. He graduated with a Ph.D in May 1994. He was supported full time by this contract from June 1993 until May 1994. His work concentrated on power combining using slot antennas and transistor oscillators.

Due to the nature of the work performed under this contract, other students have contributed to it with their work even if they have not been supported financially. A list of these students is given below:

Rhonda F. Drayton

Tom Budka

Dan Fillipovic

Steve Gearhart

Walid Ali-Ahmad

HONORS and AWARDS

During the duration of this Contracts we received the following Awards and Recognitions:

- In June 1992, Dr. Andy Engel received the **second prize in the student paper** competition by the IEEE Microwave Theory and Techniques Society during the **1992 International MTT-S Symposium** in San Diego, CA, for the paper co-authored with his advisor Prof. Linda Katehi "On the Analysis of a Transition to a layered Ridged Dielectric Waveguide".
- In June 1993, Mr. Kazem Sabetfakhri received the **third prize in the student paper** competition by the IEEE Microwave Theory and Techniques Society during the **1993 International MTT-S Symposium** in San Diego, CA, for the paper co-authored with his advisor Prof. Linda Katehi "Novel Treatment of Open Dielectric Waveguides".
- In June 1993, Mr. Kazem Sabetfakhri received the **third prize in the student paper** competition by the IEEE Antennas and Propagation Society during the **1993 International AP-S Symposium** in San Diego, CA, for the paper co-authored with his advisor Prof. Linda Katehi "On the Application of Quasi-Wavelet Expansions to Open Dielectric Waveguide Problems".
- In September 1993, Prof. Rebeiz was awarded with the **Isaac Goga Gold Medal Award** by URSI, during the 24th General Assembly Meeting in Kyoto, Japan. This award is given only once every three years by URSI to the most prominent young Senior Member of IEEE.
- In May 1994, Prof. Linda Katehi at the University of Michigan has been awarded the **Humboldt Research Award** for Senior U.S. Scientists in recognition of her accomplishments in research and teaching. According to Prof. P. Russer of the Ferdinand-Braun-Inst. f. Hochstfrequenztchnik, Berlin, this is the first Humboldt Award given to a U.S. Scientist with specialization in Electromagnetic Modeling, Development and Characterization of Monolithic Circuits and Antennas.
- In June 1994, Ms. Rhonda F. Drayton received the **first prize in the student paper** competition by the IEEE Microwave Theory and Techniques Society during the **1994 International MTT-S Symposium** in San Diego, CA, for the paper co-authored with her advisor Prof. Linda Katehi "Development of Miniature Microwave Circuit Components Using Micromachining Techniques".
- In June 1994, Dr. Steve Gearhart received the **second prize in the student paper** competition by the IEEE Microwave Theory and Techniques Society during the **1994 International MTT-S Symposium** in San Diego, CA, for the paper co-authored with his advisor Prof.Gabriel Rebeiz "A Monolithic 250 GHz Schottky-Diode Receiver".
- In Fall 1994, Prof. Katehi became a **Fellow of IEEE**.
- In October 1994, Professor Katehi received **The University of Michigan Faculty Recognition Award**, in recognition of outstanding contributions to the intellectual environment of the University.

PUBLICATIONS

PH.D DISSERTATIONS

1. "Characterization of Two-Dimensional High-Frequency Microstrip and Dielectric Interconnects," Emilie T. van Deventer, May 1992.
2. "Full-Wave Characterization of High-Frequency Non-Planar Interconnects," Andrew George Engel, Jr., June 1993.
3. "An Integrated 94 GHz Monopulse Tracking Receiver," Curtis Chih-shan Ling, September 1993.
4. "A Subharmonic Mixing Antenna for Millimeter-Wave Receivers and Oscillating Slot Antennas for Quasi-Optical Power Combining," Brian Kenneth Kormanyos, June 1994.
5. Kazem Sabetfakhri and George Ponchak have not graduated yet. They are expected to graduate in June 1995 and Winter 1996, respectively. Their dissertations will become available to ARO upon their graduation.

Theoretical Modeling of Dielectric Waveguides

Journal Publications

6. A.G. Engel and L.P. Katehi, "Frequency and Time Domain Characterization of Microstrip-Ridge Structures," IEEE Transactions on Microwave Theory and Techniques, Vol.41, No. 8, pp. 1251-1262, August 1993.
7. E.T. van Deventer and L.P.B. Katehi, "A Novel Method for the Characterization of LSE-Type Dielectric Waveguides," IEEE Transactions on Magnetics, March 1993, pp. 1584-1588.
8. Linda P.B. Katehi, "Novel Transmission Lines for the Submillimeter-Wave Region," IEEE Proceedings, Vol. 80, No. 11, pp. 1771-1787, Nov. 1992.
9. A.G. Engel, Jr. and L.P.B. Katehi, "The Effects of Finite Dielectric Layers in Multilevel Microstrip Interconnects," in press, International Journal of Microwave and Millimeter-Wave Computer-Aided Engineering.
10. Kazem Sabetfakhri and Linda P.B. Katehi, "An Integral Transform Technique for the Analysis of Planar Dielectric Structures," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-42, No. 12, pp. 1052-1062, June 1994.
11. A.G. Engel, Jr., N.I. Dib and L.P.B Katehi, "Characterization of a Shielded Transition to a Dielectric Waveguide," IEEE Transactions on Microwave Theory and Techniques, Vol. 42, No. 5, pp. 847-854, May 1994.
12. E.T. van Deventer and L.P.B. Katehi, "Application of Generalized Boundary Conditions to Submillimeter Wave and Optical Waveguides," in press Radio Science.
13. K. Sabetfakhri and L.P.B. Katehi, "Analysis of Integrated Millimeter-Wave and Submillimeter-Wave Waveguides Using Orthonormal Wavelet Expansions," IEEE Transactions on Microwave Theory and Techniques, Vol. MTT-42, No. 12, pp. 2399-2406, December 1994.

Conference Proceedings

14. A.G. Engel and L.P.B. Katehi, "Pulse Propagation on Coupled Microstrip with an Etched Groove," 1992 IEEE Topical Meeting on the Electrical Performance of Electronic Packaging, Tuscon, Arizona, April 1992, pp. 25-27.
15. A.G. Engel and L.P.B. Katehi, "On the Analysis of a Transition to a Layered Ridge Dielectric Waveguide," 1992 IEEE MTT-S International Symposium, Albuquerque, New Mexico, June 1992, pp. 983-986.
16. T.E. van Deventer and L.P.B. Katehi, "A Study of Sub-Millimeter Wave Coupled Dielectric Waveguides Using the GIE Method," 1992 IEEE MTT-S International Symposium, Albuquerque, New Mexico, June 1992, pp. 1115-1118.
17. A.G. Engel and L.P.B. Katehi, "The Role of Higher Order Modes in the Characterization of a Shielded Transition to a Dielectric Waveguide," 1993 IEEE MTT-S International Symposium, Atlanta, Georgia, June 1993, pp. 831-834.
18. Kazem Sabetfakhri and L.P.B. Katehi, "Novel Treatment of Open Dielectric Waveguides," 1993 IEEE MTT-S International Symposium, Atlanta, Georgia, June 1993, pp. 1523-1526.
19. Kazem Sabetfakhri and Linda P.B. Katehi, "On the Application of Quasi-Wavelet Expansions to Open Dielectric Waveguide Problems," 1993 IEEE AP-S International Symposium, Ann Arbor, MI, June 1993, pp. 266-269.
20. K. Sabetfakhri and L.P.B. Katehi, "Analysis of Integrated Dielectric Waveguides Using Orthogonal Wavelet Expansions," 1994 IEEE MTT-S International Symposium, San Diego, June 1994, pp. 587-590.
21. K. Sabetfakhri and L.P.B. Katehi, "Multiresolution Expansions for Efficient Moment Method Solution of Waveguiding Problems," 1994 IEEE AP-S, Seattle, WA, 1994 IEEE MTT-S International Symposium, San Diego, June 1994, pp. 24-27.
22. K. Sabetfakhri and L.P.B. Katehi, "Wavelet Analysis of Hybrid Microstrip-Dielectric Waveguide Structures," Proceedings of 1994 European Microwave Conference, pp. 1078-1083.

Presented in Symposia without Proceedings

23. K. Sabetfakhri and L.P.B. Katehi, "Characterization of Dielectric Strip Waveguides Using a Generalized Integral Equation Method,"1993 IEEE AP-S/URSI Symposium, Ann Arbor, June 1993, pp.29.
24. K. Sabetfakhri and L.P.B. Katehi, "A Study of Coupled Planar Dielectric Structures Using the Integral Transform Technique," 1994 National Meeting of URSI, Boulder, Colorado, January 1994, pp.14.
25. K Sabetfakhri and L.P.B. Katehi, "A Study of Open Dielectric Waveguides Using the Generalized Integral Equation Method," 1992 IEEE AP-S/URSI International Meeting, Chicago, Illinois, July 1992.
26. L.P.B. Katehi, "A Study of Low-Loss Transmission Lines for Sub-Millimeter Wave Applications," 1992 IEEE AP-S/URSI International Meeting, Chicago, Illinois, July 1992.

Submitted

27. K. Sabetfakhri and L.P.B. Katehi, "Fast Wavelet Analysis of 3-D Dielectric Structures Using Sparse Matrix Techniques," to be presented in the 1995 IEEE MTT-S, Orlando, FL, MAY 1995.
28. K. Sabetfakhri and L.P.B. Katehi, "FWA for Moment Analysis of Electromagnetic Problems," to be presented in the 1995 ACES, Monterey, CA, March 1995.
29. K. Sabetfakhri and L.P.B. Katehi, "Modeling of Microwave Circuits Using Wavelet Concepts," submitted for the 1995 COMPUMAG International Conference on the Computation of Electromagnetic Fields, Berlin, Germany, July 1995.

Experimental Characterization of Dielectric Waveguide Transmission Lines and Antennas

Symposia Proceedings

30. George Ponchak and Linda P.B. Katehi, "Development of Leaky Wave Antennas for Layered Ridge Dielectric Waveguide," 1993 IEEE AP-S International Symposium, Ann Arbor, MI, June 1993, pp. 580-583.
31. G.E Ponchak, N.I. Dib and L.P.B. Katehi, "A Novel Transition Between a Rectangular Waveguide and Layered Ridge Waveguide," Proceedings of 1994 European Microwave Conference, September 1994, Cannes, France, pp. 1933-1937.

Submitted

32. G.E. Ponchak, N.I. Dib and L.P.B. Katehi, "Design and Analysis of Transitions from Rectangular Waveguide to Layered Ridge Dielectric Waveguide," submitted to IEEE Transactions of Microwave Theory and Techniques.

94 GHz Monopulse Receiver

Journal Publications

33. C.C. Ling and G.M. Rebeiz, "94 GHz integrated horn monopulse antennas," IEEE-Transactions Antennas Propagation., vol. 40, pp. 981-984, August 1992.
34. G.M. Rebeiz, "Millimeter-wave and terahertz integrated-circuit antennas," Invited paper, IEEE Proceedings - Special Issue on Space Terahertz Technology, vol. 80, pp. 1748-1770, Nov. 1992.
35. C.C. Ling and G.M. Rebeiz, "A 94 GHz planar monopulse receiver," IEEE-Microwave and Guided Wave Letters, Vol. 3, No. 10, pp. 358-360, October 1993.
36. T.P. Budka, M.W. Trippe, S. Weinreb and G. M. Rebeiz, "A 75 to 115 GHz quasi-optical amplifier," IEEE-Microwave Theory and Techniques, Vol. 42, No. 5, pp. 899-901, May 1994.
37. B.K. Kormanyos and G.M. Rebeiz, "Oscillator design for maximum added power efficiency," IEEE- Microwave and Guided Wave Letters, Vol. 4, No. 6, pp. 205-207, June 1994.

38. B.K. Kormanyos and G.M. Rebeiz, "20 GHz power combining slot-oscillator array," IEEE- Microwave and Guided Wave Letters, Vol. 4, No. 7, pp. 226-228, July 1994.

39. C.C. Ling and G.M. Rebeiz, "A 94 GHz integrated monopulse tracking receiver," IEEE-Microwave Theory and Techniques, Vol. 42, No. 10, pp. 1863-1871, October 1994.

Conference Papers

40. C.C. Ling and G.M. Rebeiz, "94 GHz integrated monopulse antennas," IEEE/AP-S Int'l. Sump., pp. 987-990, London, Ontario, June 1991.

41. G. M. Rebeiz, "Antennas and Devices: The marriage of the future," Invited paper, presented at the 1991 International Device Research Symposium, Charlottesville, Virginia, December 1991.

42. G. M. Rebeiz, "Integrated submillimeter-wave antennas and receivers," Invited paper IEEE International. Microwave Symposium, Albuquerque, New Mexico, pp.1145-1149, June 1992.

43. C.C. Ling and G.M. Rebeiz, "Advances in 94 GHz integrated horn monopulse antennas," IEEE-APS Symposium, Chicago, Illinois, pp. 2167-2170, 1992.

44. G.M. Rebeiz, C.Y.Chi, B.K. Kormanyos, G.V. Eleftheriades and W.Y. Ali-Ahmad, "Millimeter-wave integrated horn antennas and quasi-optical balanced receivers," International. Symposium on Antennas and Propagation, Sapporo, Japan, pp. 1137-1140, Sept. 1992.

45. T.P. Budka, M.W. Trippe, S. Weinreb and G. M. Rebeiz, "A 75 to 115 GHz quasi-optical amplifier," Fourth Int'l. Conf. on Space Terahertz Tech., Los Angeles, California, pp. 104-112, March 1993.

46. T.P. Budka, M.W. Trippe, S. Weinreb and G.M. Rebeiz, "A 75 to 115 GHz quasi-optical amplifier," IEEE-APS Symposium, Ann Arbor, Michigan, pp. 576-579, June 1993.

47. C.C. Ling and G.M. Rebeiz, "A 94 GHz integrated monopulse receiver," IEEE-APS Symposium, Ann Arbor, Michigan, pp. 608-611, June 1993.

48. B.K. Kormanyos, L.P. Katehi and G.M. Rebeiz, "Power combining designs with cpw-fed slot antennas," URSI Meeting, Ann Arbor, Michigan, p. 142, June 1993.

49. B.K. Kormanyos and G.M. Rebeiz, "20 GHz power combining slot-oscillator array," IEEE - Antennas and Propagation Symposium, pp. 840-843, Seattle, Washington, June 1994.

Conference/Meeting Papers with no Proceedings:

50. G.M. Rebeiz, "Advances in integrated active antennas and receivers at millimeter-wave frequencies," Invited paper presented at the 24'th General Assembly Meeting of URSI, Japan, August 1993.

51. C.C. Ling and G.M. Rebeiz, "A 94 GHz integrated monopulse tracking receiver with IF beam control," Workshop on Millimeter-Wave Power Generation and Beam Control, Alabama, Sept. 1993.

52. G.M. Rebeiz, "Millimeter-Wave receivers for automotive applications," IEEE International. Microwave Symposium, Workshop on Automotive Systems, San Diego, CA, June 1994.

A BRIEF ANALYSIS OF THE RESEARCH FINDINGS

The work performed under this contact can be divided into two subjects: (a) The theoretical and experimental characterization of dielectric waveguide antennas for W-band applications (b) The development of a 94GHz monopulse receiver. The performed study has been extensively described in a number of manuscripts which have been published, have been submitted for publication or are under preparation a list of which has been provided above. In addition to these publications, a brief analysis is meant to critically review the work, emphasize the findings, and describe the extensions and new research efforts which were developed as a consequence of this award.

(a) Theoretical and Experimental Characterization of Dielectric Waveguide Antennas for W-Band Applications

The theoretical and experimental parts of this study have been performed separately and for this reason are described in separate sections:

- *Theoretical Study*

Andrew Engel

Emilie van Deventer

Kazem Sabetfakhri

The theoretical study started with Andy Engel's work who identified dielectric waveguide cross sections which could provide very small size and very good power confinement. These dielectric waveguide have cross sections which are made of layered materials with very different indices of diffraction. The characteristic of this structure is that the wave is guided by the low index layer and has a height and width equal to a small fraction of the wavelength [6], [9], [17]. These characteristics are in contrast to the conventional dielectric waveguides which propagate in the higher index material and are comparable to one wavelength in height and width. This work by Andy led the experimental characterization as it will be described later, but also initiated an effort which eventually led to the development of a formulation based on multiresolution analysis and the use of wavelets as basis functions. The analysis of the dielectric structures in this effort was based on an integral equation method where the Green's function was calculate numerically using a method of moments technique [11], [14], [15].

Despite the accuracy of the solution and the capability of the approach to provide a very complete mode diagram for the considered dielectric structures, computer memory requirements and computation times were running exceptionally high, thus, making the analysis of complex three-dimensional structures practically impossible. As a result another effort was initiated by Emilie van Deventer towards the end of her dissertation were the integral equation solved by Andy Engel was transformed to a lower-dimensionality domain by appropriate use of high-order boundary conditions [7], [16]. This transformed integral equation was solved using subsectional basis functions such as pulses, ovelapping sinusoids and overlapping triangular functions. This development was first attempted in shielded dielectric waveguides and it showed that such a transfor-

mation was possible and very successful [12]. However, there was one problem associated with this effort. In specific dielectric waveguide cross-sections we noticed the development of spurious solutions which we could not eliminate despite extensive efforts to change the basis functions and the method of moments scheme.

With Emilie's graduation, the goal to eliminate the spurious solutions was undertaken by Kazem Sabetfakhri. At first, he applied the same concept of transforming the integral equation to a lower dimensionality to open dielectric waveguide problems. His effort indicated that a mathematically exact transformation can be achieved easily in the spectral domain and can also be solved very effectively using the method of moments as long as the basis functions satisfy specific conditions. These functions should be entire domain (infinite support), should have higher order continuous derivatives (at least up to two) and should have a shift and dilation built into them. In fact these properties make a function look like a wavelet. This realization led us into using wavelets-like functions such as Hermite polynomials for the solution of the transformed integral equation in the spectral domain and we realized that this choice of basis function eliminated spurious modes and provided very accurate results for a vary small number on unknowns. Specifically, dielectric waveguide problems could be calculated with two basis functions only were other conventional integral equation solutions would require 45 basis functions [10], [18], [19], [23]-[25].

The results of this effort led us into using wavelet functions in the regular integral equation in an effort to provide solutions to a broader variety of problems for which the previously applied transformation was difficult to implement. Since then we have been able to develop a methodology based on a complete application of multiresolution analysis with scaling as well as wavelet functions as the basis functions. This methodology has been extensively applied to dielectric waveguide problems and it is now applied to planar circuit and antenna problems [13], [20]-[22], [27]-[29]. In this manner we were able to solve the generalized integral equation for these problems using multiresolution analysis and we were able to prove that the resulting matrices both in two and three-dimensional problems are highly sparse (97%-99%). This allows for an easy and fast solution of the resulting matrix equation using iterative techniques such as the conjugate gradient method with an FFT algorithm built into it. This was the first breakthrough of this work which in fact proved that matrix inversion is not the limiting factor in the integral equation formulation. Furthermore, we have been to conclude that other properties of the wavelet functions allow for the development of a generalized modeling tool which is based for the first time on the integral equation approach. Specifically, radiation problems or waveguiding problems can now be solved by this technique which in a way competes very favorably with the Finite Element and the Finite Difference Methods. The major advantages come from the following realizations:

- The radiation conditions, in the case of open structures, and the boundary conditions on the walls of waveguide or cavity, for the case of shielded structures, can be satisfied by the Green's function of the problem. Therefore, there is no need for a numerical implementation of the boundary conditions.
- Due to the above only subsections of the computational volume of interest are discretized in contrast to FEM and FDFD and FDTD which discretize all of this volume. This results in tremendous savings in the number of unknowns introduced by the solution.

- The application of wavelets leads to highly sparse matrices due to the special properties of these basis functions. The sparsity of the matrix allows for the use of inversion techniques similar to FEM.
- As with FEM, this sparsity can be predicted in advance thus permitting the computation of only those elements which have numerically important contributions.
- The computation of these elements can be accelerated tremendously with the use of the fast wavelet algorithm (FWA).
- Multiresolution analysis allows for the use of a variety of Green's functions depending on the problem and the intended generalization of the code. For example, the use of the free-space Green's function can lead to a very general tool for the analysis of any open geometry. The use of the cavity Green's function can lead to a tool that can handle any shielded geometry. The use of more complex Green's functions can allow generalizations within subsets. For example, the Green's function for a grounded substrate can allow the solution of any printed antenna problem etc.

In conclusion, this technique combines all the advantages of the Integral equation and Finite Element methods while it is free from ambiguities arising from virtual boundaries, is highly stable numerically and highly accurate computationally. Furthermore, it has the capability to provide schemes for adaptive meshing and error control. The work performed under this contract helped in identifying a very new and dynamic area in computational EM with a strong potential to lead to very general EM tools. The student who performed this work will graduate in May 1995 and is interested in creating his own company with a goal to develop the software to a point where a software house like COMPACT can take it over, develop it further and commercialize it.

- *Experimental Study*

George Ponchak

This effort concentrated on the experimental development of layered dielectric waveguides for Ka and W-band applications. During the past two years, our study showed that the development of layered waveguides in Ka band can only be performed through a non-monolithic approach using layers of duroid of dielectric constants 2.5 and 10.0. These dielectric waveguides were measured and the experiments confirmed the theoretical claims described in the previous section. Specifically, these waveguides, proved that this layered arrangement can provide very good field confinement, low loss and very small size. Furthermore, these waveguides were used to develop leaky wave antennas, the performance of which was measured successfully and results were presented in 1993 IEEE AP-S Symposium [30]. As part of this effort we developed an optimum transition from a rectangular waveguide to a dielectric ridge waveguide with the smallest demonstrated insertion loss over the whole band. This transition had a loss of less than -17 dBs over the frequency band of interest. The measurements were confirmed with theoretical data computed by our own group using a finite difference time domain code and the results from this study were presented in the 1994 European Conference [31], [32]. Since then the effort concentrated on a similar application in W band.

This study is still going on at NASA Lewis and has shown that it is possible to develop layered dielectric waveguides using Si and quartz but with a low yield at the present time. However, we have been able to make dielectric waveguides and fabricate transitions to dielectric waveguide from rectangular waveguide and microstrip, in addition to bends and open/short circuit terminations. At the present time, George Ponchak is trying to measure these geometries in W band with a measurement system available for use at NASA Lewis.

Most of our effort in this subtask concentrated on the use of the right materials and appropriate fabrication techniques which could reliably provide dielectric waveguide components and antennas at W band. While this has been the bottleneck for this work, we have been able to successfully come to the point where these waveguides have now been fabricated. The student who primarily works under this task has a fellowship from NASA and will continue with this effort until he graduates in early 1996. His objectives are to complete the measurement of dielectric waveguide loss in W band, measure the performance of the fabricated components and complete his dissertation with the development of a W-band dielectric waveguide array.

Our efforts in this area, both theoretical and experimental have attracted the attention and interest of ThermoTrex Corporation in San Diego. This company wants to collaborate with us to develop a W-band dielectric waveguide array.

(b) Integrated 94 GHz Monopulse Receiver

Curtis Ling

We have built a planar focal-plane monopulse receiver at 94 GHz. The receiver consists of four planar antennas, each with its own RF mixer, and occupies an area less than 1.5-cm square. The monopulse receiver can be integrated monolithically in an even smaller area (around 1cm-square). The monopulse system is based on mixing the received RF signal with a planar local oscillator to 200 MHz and then using an IF monopulse processing network for obtaining the sum and difference patterns. The monopulse receiver resulted in excellent performance, with azimuth and elevation difference patterns showing a null depth of 30 dB. The receiver chip was used to instantaneously track a 94 GHz source with a tracking resolution of the order of 0.02 degrees. The receiver can be placed at the focal plane of a lens or parabolic reflector to result in very high gain patterns and high tracking resolution. Perhaps the most important aspect of the work is that Mitshubishi Electronics has built a similar system using essentially the same idea. This work is been extended with funding from the Army Research Office (ARO DAAh04-94-G-0352. Duration: June 1994 to June 1996) to build a more efficient and higher performance system at 94 GHz with a wider IF bandwidth (3 GHz).

20 GHz Power Combining Using Slot-Antenna Oscillators

Brian Kormanyos

We have also worked on power combining applications using coplanar waveguide (cpw)-fed slot antenna oscillators. In this work, a large amount of oscillators are combined together to result in a high power source. The problems encountered with such systems is the non-linear interaction in the coupled-oscillators. As a single oscillator, we use a slot-antenna with a single microwave transistor designed to oscillate at 20 GHz. We have successfully combined a 2x2 array of these slot-antenna oscillators at 20 GHz to generate a total radiated power of 70 mW with a dc-RF efficiency of 15%. The power combining efficiency was 100%. Since the antennas are placed on a dielectric lens and therefore result in a high-gain pattern, the effective radiated power is around 4.5W. This configuration does not suffer from substrate mode problems and therefore can be easily extended to 94 GHz power combining systems.